APPENDIX B

(VERSION OF SUBSTITUTE SPECIFICATION EXCLUDING CLAIMS WITH MARKINGS TO SHOW CHANGES MADE)

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APPLICATION FOR LETTERS PATENT

for

FIELD EMISSION TIPS AND METHODS FOR FABRICATING THE SAME

Inventors:
Guy T. Blalock
Sanh D. Tang
Zhaohui Huang

Attorneys:
Joseph A. Walkowski
Registration No. 28,765
Brick G. Power
Registration No. 38,581
TRASKBRITT, PC
P.O. Box 2550
Salt Lake City, Utah 84110
(801) 532-1922

TITLE OF THE INVENTION

FIELD EMISSION TIPS AND METHODS FOR FABRICATING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is a divisional of application Serial No. 09/559,153, filed April 26, 2000, pending.

BACKGROUND OF THE INVENTION

[0002] Field of the Invention: The present invention relates to field emitters and methods of fabricating the same. More particularly, the present invention relates to forming field emission tips by the use of facet etching.

[0003] State of the Art: Various types of field emitters are used in a variety of devices, from electron microscopes to ion guns. However, one of the most prevalent commercial applications of field emitters is flat panel displays, such as cold cathode field emission displays ("FEDs") used for portable computers and other lightweight, portable information display devices.

[0004] As illustrated in FIG. 18, an exemplary flat panel cold cathode FED 200 comprises a flat vacuum cell 202 having a cathode 204 and an anode 206 spaced apart from one another in a mutually parallel relationship. The cathode 204 comprises a conductive or semiconductive first material 208, such as silicon, disposed on a substrate 212, such as a semiconductive or dielectric material, and an array of minute field emission tips 214 distributed across the first material 208. The anode 206 comprises a conductive second material 216 disposed on an interior surface of a transparent plate 218[,] and a phosphorescent or fluorescent material 222 is coated on the conductive second material 216. A conductive structural element, called a gate 224, is disposed in the space between the cathode 204 and anode 206. The gate 224 is generally formed atop a grid of dielectric material 226 deposited on the cathode 204. The field emission tips 214 reside within openings in the gate 224 and in the dielectric material 226, such that the gate 224 surrounds each field emission tip 214. The gate 224 acts as a low-potential anode (i.e., lower potential than the anode 206), such that when a voltage differential, generated

by a voltage source 228, is applied between the cathode 204 (strong negative charge), the gate 224 (weak positive charge), and the anode 206 (strong positive charge), a Fowler-Nordheim electron emission is initiated, resulting in a stream of electrons 232 being emitted from the field emission tips 214 toward the phosphorescent or fluorescent material 222. The electron stream 232 strikes and stimulates the phosphorescent or fluorescent material 222. The stimulated phosphorescent or fluorescent material 222 emits photons (light) (not shown) through the conductive second material 216 and the transparent plate 218 to form a visual image.

[0005] FIGs. 19-23 illustrate a conventional method of forming a field emission tip. As shown in FIG. 19, a substrate of conductive or semiconductive material 252, such as silicon, is deposited or formed over a dielectric support 254. A mask material is patterned (such as by lithography) to define a mask element 256 at the position of the emission tip 258 to be formed. The conductive or semiconductive material 252 is then etched, such as by a wet etch or an isotropic dry etch, which "undercuts" the mask element 256 to form a sharp field emission tip 258 beneath the mask element 256, as shown in FIG. 20. The mask element 256 is then removed, as shown in FIG. 21. Although such a method is commonly used to form field emission tips 258, the method has drawbacks. For example, as shown FIG. 22, if the etching is halted too soon, inefficient, blunt field emission tips 262 are formed. Further, if the etching is not halted soon enough, the mask element 256 is undermined and the field emission tips 264 formed are short and may be ineffective, as shown in FIG. 23 (shown with the mask element 256 collapsed onto the conductive or semiconductive material 252). In other words, the short field emission tip 264 may not be close enough to a gate in a field emission display to generate a sufficient stream of electrons striking the phosphorescent or fluorescent material on the anode to stimulate the material and form a visual image.

[0006] Other field emission tip formation techniques which do not involve isotropic etching are also known. For example, U.S. Patent 5,312,514, issued May 17, 1994 to Kumar ("the Kumar patent"), relates to forming field emission tips by distributing a discontinuous etch mask material across an electrically conductive material layer. The discontinuity of the etch mask material forms random openings therein. The etch mask material is selected such that the electrically conductive material layer will etch at a faster rate than the etch mask material (at least

twice the rate) when the electrically conductive material layer is ion etched. The ion etch is performed until all of the etch mask is removed, which results in v-shaped valleys in the electrically conductive material defining peaked field emission tips therebetween. Further, the Kumar patent discusses using a low work function material for the electrically conductive material layer and also discusses depositing a low work function material over the electrically conductive material after the formation of the field emission tips. Although the method taught in the Kumar patent eliminates the use of an isotropic etch to form field emission tips, it lacks control over the field emission tip distribution and dimensions. The discontinuous layer of etch mask material results in a nonuniform distribution of field emission tips, since the positions of the openings in the discontinuous layer cannot be controlled. Furthermore, the discontinuous layer of etch mask material results in non[-]uniform dimensions between the field emission tips, since the thickness difference across the discontinuous layer cannot be controlled. In other words, the field emission tips formed in areas where less etch mask material existed over the conductive material will be shorter than in other areas. Moreover, since the etch mask material is a discontinuous layer rather than a patterned mask, the size or diameter of the field emission tips formed cannot be controlled.

[0007] Thus, it can be appreciated that it would be advantageous to develop a technique which would result in novel field emission tips having uniform distribution and uniform, precise dimensions.

SUMMARY OF THE INVENTION

[0008] The present invention relates to field emitters and methods of fabricating the same, wherein the field emission tips of the field emitters are formed by utilization of a facet etch.

[0009] In an exemplary method of the present invention, an etch mask is patterned on a conductive substrate material in the locations desired for subsequently formed field emission tips. The etch mask can be patterned in various shapes in order to achieve a desired field emission tip structure. For example, a circular mask element will result in a conical field emission tip, a triangular mask element will result in a tetrahedral field emission tip, a square mask element will result in a pyramidal field emission tip, and so on. The conductive substrate material is anisotropically etched to translate the shape of the mask into the underlying conductive substrate

material, which forms a vertical column having a cross-section with the same shape as the mask element, from the conductive substrate material. The anisotropic etch is conducted for a predetermined duration of time, which will result in a column of a specific height required for the subsequently formed field emission tip. The etch mask element is then removed (optional) and the vertical column is facet etched to form the field emission tip.

[0010] The facet etching is generally performed in a chamber in which ions can be accelerated to strike a substrate, such as reactive ion etchers, magnetically enhanced reactive ion etchers, low pressure sputter etchers, and high density source etchers. As opposed to anisotropic etches, such as ion etching or plasma etching processes, in which ions strike the surface of the substrate substantially perpendicular to result in a vertical etch, a facet etch results in ions dispersed in a fashion which results in the ions striking 90 degree features (i.e., corners) of structures on the substrate at a rate which is about four to five times that of the rate at which ions strike substantially planar surfaces (e.g., surfaces laying substantially perpendicular to the ion emission source) on the substrate. In fact, with facet etching, the planar surfaces experience very little substrate loss. The facet etch creates a gradual slope of about 45 degrees at the corners of the structures on the substrate.

[0011] The facet etch is preferably performed in a reactive ion etcher wherein the substrate is placed on a cathode within a high-vacuum chamber into which etchant gases are introduced in a controlled manner. A radio frequency power source creates a plasma condition in the high-vacuum chamber which generates ions. The walls of the high-vacuum chamber are grounded to allow for a return radio frequency path. Due to the physics of the radio frequency powered electrodes, a direct current self-bias voltage condition is created at the substrate location on the cathode, which causes the generated ions in the plasma to accelerate toward and strike the substrate. The etchant gases utilized in the facet etch are preferably inert gases, including, but not limited to, helium, argon, krypton, and xenon. These inert gases have been found to enhance the uniformity of the facet etch process. It is, of course, understood that any other suitable gas or mixture of gases which are inert with respect to the material of the substrate may also be used.

[0012] Thus, the present invention eliminates the use of isotropic etching to form field emission tips and, thereby, eliminates the problems associated with isotropic etching. Although

the present invention requires more steps than the typical isotropic etching technique of forming field emission tips, the methods of the present invention result in more uniform distribution, size, and height for the field emission tips, since the location and size of the etch mask elements defining the tip locations, as well as the depth of the anisotropic etch, can be precisely controlled. This precise control results in a field emission tip array having regular uniform tip spacing as well as precise, uniform tip height, thus improving the performance and reliability of the field emission display device formed therefrom. Furthermore, the precise control of the tip spacing allows the tips to be packed closer to one another, which results in a higher fidelity screen with more pixels per square inch.

[0013] The present invention also allows for low work function materials to be easily incorporated into the field emission tips. The overall work function of a field emission tip affects its ability to effectively emit electrons. The term "work function" relates to the voltage (or energy) required to extract or emit electrons from a field emission tip. The lower the work function, the lower the voltage required to produce a particular amount of electron emission. Thus, the incorporation of low work function materials in field emission tips can substantially improve their performance for a given voltage draw.

[0014] A variety of low work function materials can be incorporated into the field emission tips of the present invention. Such low work function materials include, but are not limited to, $AlTiSi_x$ (aluminum titanium silicide [wherein x is generally between 1 and 4]), $TiSi_xN$ (titanium silicide nitride), TiN (titanium nitride), Cr_3Si (tri-chromium mono-silicon), TaN (tantalum-nitride), or the like. Moreover, other low work function materials, such as metals including cesium (Ce), and cermets including $Cr_3Si–SiO_2$ (tri-chromium mono-silicon silicon-dioxide), $Cr_3Si–MgO$ (tri-chromium mono-silicon magnesium-oxide), $Au–SiO_2$ (gold silicon-dioxide), and Au–MgO (gold magnesium oxide), may also be used.

[0015] One embodiment of the invention for incorporating low work function materials into the field emission tips according to the present invention involves depositing a low work function material on a conductive substrate material. The low work function material may be deposited by ion beam sputtering, laser deposition, evaporation, chemical vapor deposition (CVD), and sputtering. An etch mask is then patterned on the low work function material to

form discrete mask elements in the locations desired for the field emission tips to be formed. The low work function material and conductive substrate material are then anisotropically etched to form a column under each etch mask element from the conductive substrate material and a portion of the low work function material. The etch mask elements are then removed (optional). The vertical columns, capped with the low work function material, are then facet etched to form an array of low work function material-tipped field emission tips. Redeposition material, comprising a mixture of material from the vertical column substrate material and the low work function material, generated by the facet etch collects in corners at junctions of the vertical columns and the base conductive substrate during the facet etch.

[0016] Another embodiment of the invention for incorporating low work function materials into the field emission tips according to the present invention involves incorporating a sacrificial layer to assist the removal of redeposition material from the field emission tip. As with the previously discussed embodiments of the present invention, a low work function material is deposited on a conductive substrate material. An etch mask is patterned to form etch mask elements on the low work function material in the locations desired for the field emission tips to be formed. The low work function material and conductive substrate material are then anisotropically etched under such mask elements to form vertical columns from the conductive substrate material capped by a portion of the low work function material. The etch mask elements are then removed (optional). A sacrificial material, such as silicon dioxide or tetraethyl orthosilicate (TEOS), is then conformally deposited over the array of vertical columns, each capped with the low work function material, to form a covered structure. The covered structures are then facet etched to form an array of low work function material-tipped field emission tips. Redeposition material generated by the facet etch, comprising a mixture of material from the vertical column, the low work function material, and the sacrificial material, collects in exposed corners of the sacrificial material at a junction of the vertical column and the conductive substrate during the facet etch. Although such redeposition material would be difficult to remove if deposited directly on the conductive material of the tips and underlying substrate, the presence of the sacrificial material under the redeposition material allows the redeposition material to be easily

removed using a clean-up technique, such as a hydrofluoric acid (HF) dip or a diluted HF dip, as known in the art. The mask element is then removed, as known in the art.

[0017] Thus, the present invention allows for easy incorporation of a variety of materials on top of the field emission tips to improve their performance.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] While the specification concludes with claims particularly pointing out and distinctly claiming that which is regarded as the present invention, the advantages of this invention can be more readily ascertained from the following description of the invention when read in conjunction with the accompanying drawings, in which:

[0019] FIGs. 1-4 are cross-sectional views of one embodiment of a method for forming field emission tips according to the present invention;

[0020] FIG. 4A is a cross-sectional schematic representation of a field emission tip, depicting an apex having a measurable lateral width;

[0021] FIGs. 5-9 are cross-sectional views of another embodiment of a method for forming field emission tips according to the present invention;

[0022] FIGs. 10-16 are cross-sectional views of still another embodiment of a method for forming field emission tips according to the present invention;

[0023] FIG. 17 is a cross-sectional view of a cold cathode field emission display including field emission tips formed by a method according to the present invention;

[0024] FIG. 18 is a cross-sectional view of an exemplary conventional cold cathode field emission display;

[0025] FIGs. 19-21 are cross-sectional views of a conventional method of forming a field emission tip;

[0026] FIG. 22 is a cross-sectional view of a field emission tip formed by the conventional method illustrated in FIGs. 19-21 when the tip etching is prematurely terminated; and

[0027] FIG. 23 is a cross-sectional view of a field emission tip formed by the conventional method illustrated in FIGs. 19-21 when the tip etching is not terminated prior to over-etching the tip.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0028] FIGs. 1-16 illustrate various methods of forming field emission tips according to the present invention. It should be understood that the illustrations are not meant to be actual views of any particular field emission device, but are merely idealized representations which are employed to more clearly and fully depict the formation of field emission tips of the present invention than would otherwise be possible. Additionally, elements common to FIGs. 1-16 retain the same numerical designation.

[0029] FIGs. 1-4 illustrate one embodiment for forming field emission tips according to the present invention. As shown in FIG. 1, an etch mask material, such as a photoresist material, is patterned by photolithography to define an etch mask element 104 on a substrate 102, such as a wafer of semiconductor material (e.g., silicon) or a silicon on insulator (SOI) type substrate, such as a silicon on glass (SOG) or silicon on sapphire (SOS) substrate. The substrate 102 may also be conductive material layered over a dielectric substrate (not shown). The substrate 102 is then anisotropically etched by dry etch techniques, such as physical sputtering or plasma etching, to form from the substrate 102 and, under etch mask element 104, a vertical column 106 of substantially constant cross-section and exhibiting substantially vertical sidewalls 107 relative to a plane of substrate 102, as shown in FIG. 2. For example, the anisotropic etch may be a plasma dry etch conducted at a power of about 250 watts, at a pressure of about 85 mTorr, and employing an etchant gas mixture comprising hydrobromic acid (HBr) gas, delivered at a rate of about 10 sccm, and chlorine gas (Cl_2), delivered at a rate of about 60 sccm. The etch mask element 104 is removed from the vertical column 106, as shown in FIG. 3. The vertical column 106 is facet etched to form a substantially pointed field emission tip 108 with a sharp apex 109, as shown in FIG. 4. As an example, the facet etch may include a reactive ion etch (RIE) or a magnetically enhanced reactive ion etch (MERIE) conducted at a power of about 600 watts to about 800 watts, at a pressure of about 20 mTorr to about 50 mTorr, under a magnetic field of

about 40 gauss, and employing an etchant gas comprising Argon (Ar) delivered at a rate of about 30 to about 70 sccm. The facet etch is continued until a tip with a sharp apex 109 is defined, which for a silicon column of about 1 micron diameter is approximately 100-200 seconds, depending on the RF power setting used for the facet etch.

[0030] As shown in FIG. 4A, apex 109 may have a measurable lateral width W. Preferably, the sharp apex 109 has a lateral width W of less than about 100 nm. The width or diameter of apex 109 may be as small as about 50 nm or less.

[0031] As shown in FIG. 4, during the facet etch, redeposition material 110, which includes the material from the etched vertical column 106, may collect adjacent substantially vertical sidewall 107 of field emission tip 108.

[0032] FIGs. 5-9 illustrate another embodiment for forming field emission tips according to the present invention. As shown in FIG. 5, a low work function material 112, preferably $AlTiSi_x$ (aluminum titanium silicide), $TiSi_xN$ (titanium silicide nitride), or TiN (titanium nitride), is deposited on a substrate 102 by known processes, such as by the use of chemical vapor deposition (CVD) or sputtering.

[0033] An etch mask material is patterned to define etch mask element 104 on the low work function material 112, as shown in FIG. 6. The low work function material 112 and substrate 102 are then anisotropically etched by known dry etch techniques (e.g., high density plasma etching, RIE, magnetic ion etching (MIE), MERIE, plasma etching (PE), point plasma etching, plasma enhanced reactive ion etching (PERIE), or electron cyclotron resonance (ECR)) to form a substantially constant cross-section vertical column 106 from the portions of the substrate 102 and the low work function material 112 protected by etch mask element 104, as shown in FIG. 7. The etch mask element 104 is then removed, as shown in FIG. 8. The vertical column 106 capped with the low work function material 112 is then facet etched by the same techniques as described with respect to the previously disclosed method illustrated in FIGs. 1-4 to form a field emission tip 114 with low work function material 112 at the top portion thereof, as shown in FIG. 9. As also shown in FIG. 9, a redeposition material 116 resulting from the facet etch, comprising a mixture of material from the vertical column 106 and the low work function

material 112, may, during the facet etch, collect in corners 118 at a junction between the substantially perpendicular portion of the periphery of field emission tip 114 and substrate 102.

[0034] FIGs. 10-16 illustrate still another embodiment for forming field emission tips according to the present invention. As shown in FIG. 10, a low work function material 112 is deposited on a substrate 102. An etch mask material is patterned to form etch mask element 104 on the low work function material 112, as shown in FIG. 11. The low work function material 112 and substrate 102 are then anisotropically etched by known techniques (e.g., high density plasma etching, RIE, MIE, MERIE, PE, point plasma etching, PERIE, or ECR) to form a vertical column 106 of substantially constant cross-section from the portion of the substrate 102 and the low work function material 112 protected by etch mask element 104, as shown in FIG. 12. Etch mask element 104 is then removed, as shown in FIG. 13. A sacrificial material 122, such as silicon dioxide or tetraethyl orthosilicate (TEOS), is then conformally deposited over the vertical column 106 capped with the low work function material 112 to form a covered structure 124, as shown in FIG. 14. The covered structure 124 is then facet etched, such as by the same techniques as those described previously herein with respect to FIGs. 1-4, to form a low work function material-tipped field emission tip 130, as shown in FIG. 15. As also shown in FIG. 15, a redeposition material 126 produced during the facet etch, comprising a mixture of material from the vertical column 106, the low work function material 112, and the sacrificial material 122, collects in exposed corners 128 of the sacrificial material 122 at a junction of the vertical column 106 and the base substrate 102 during the facet etch. Although such redeposition material 126 would be difficult to remove if deposited directly on the vertical column 106 and the base substrate 102 surfaces, the presence of the sacrificial material 122 under the redeposited material 126 allows the redeposition material 126 to be removed with a clean-up technique, as illustrated in FIG. 16, such as by a hydrofluoric acid (HF) dip or diluted HF dip, as known in the art. The mask element is then removed, as known in the art, to expose a cleaned, low work function material-tipped field emission tip 132.

[0035] FIG. 17 illustrates an exemplary flat panel cold cathode FED 150 including low work function material-tipped field emission tips 164 formed by a method of the present invention. The flat panel cold cathode FED 150 is similar in structure arrangement to the

conventional flat panel cold cathode FED 200 illustrated in FIG. 18 and comprises a flat vacuum cell 152 having a cathode 154 and an anode 156 spaced a distance apart from one another. The cathode 154 comprises a first conductive substrate material 158 disposed on a dielectric support 162, and the low work function material-tipped field emission tips 164 are distributed across the first conductive substrate material 158. The anode 156 comprises a second conductive material 166 disposed on an interior surface of a transparent plate 168 and a phosphorescent or fluorescent material 172 coated on the second conductive material 166. A gate 174 is formed atop a grid of dielectric material 176 deposited on the cathode 154. The low work function material-tipped field emission tips 164 reside within openings in the gate 174 and in the dielectric material 176, such that the gate 174 surrounds each low work function material-tipped field emission tip 164. The gate 174 acts as a low-potential anode (i.e., lower potential than the anode 156), such that when a voltage differential, generated by a voltage source 178, is applied between the cathode 154 (strong negative charge), the gate 174 (weak positive charge), and the anode 156 (strong positive charge), a Fowler-Nordheim electron emission is initiated, resulting in a stream of electrons 182 being emitted from the low work function material-tipped field emission tips 164 toward the phosphorescent or fluorescent material 172. The electron stream 182 strikes and stimulates the phosphorescent or fluorescent material 172. The stimulated phosphorescent or fluorescent material 172 emits photons (light) (not shown) through the second conductive material 166 and the transparent plate 168 to form a visual image.

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Having thus described in detail preferred embodiments of the present invention, it is to be understood that the invention defined by the appended claims is not to be limited by particular details set forth in the above description as many apparent variations thereof are possible without departing from the spirit or scope thereof.